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Naturally Occurring and Forced Azimuthal Modes in a Turbulent Jet

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NATURALLY OCCURRING AND FORCED AZIMUTHAL MODES IN A TURBULENT JET

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SUMMARY

Naturally occurring instability modes in an axisymmetric jet were studied using the modal frequency spectrum technique. The evolution of the modal spectrum was obtained for a jet with a Reynolds number based on diameter (Re(D)) of 400 000, for both laminar and turbulent nozzle exit boundary layers. In the early evolution of the jet, the axisymmetric mode was predominant, with the azimuthal modes growing rapidly but dominating only after the end of the potential core. The growth of the azimuthal modes was observed closer to the nozzle exit for the jet in the laminar boundary layer case than for the turbulent.

Based on the results from these naturally occurring jet instability mode experiments, target modes for efficient excitation of the jet were determined and two cases of excitation were studied. First, the jet was excited simultaneously by two helical modes, m = +1 and m = -1 at a Strouhal number based on jet diameter (St(D)) of 0.15 and the axisymmetric mode, m = 0 at a St(D) of 0.6. Second, m = +1 and m = -1 at St(D) = 0.3 and m = 0 at St(D) = 0.6 were excited simultaneously. The downstream evolution of the hydrodynamic modes and the spreading rate of the jet were documented for each case. Higher jet spreading rates, accompanied by distorted jet cross-sections, were observed for the cases where combinations of axisymmetric and helical forcings were applied.

NOMENCLATURE

a_o, a_m, b_m	constants
D	nozzle diameter
F	velocity cross-spectral function
f	frequency

M	Mach number
m	azimuthal mode number
R	nozzle radius
Re	Reynolds number
r	radial distance
St	Strouhal number $St(d) = fD/U_j$; $St(\theta) = f*(\theta)/U_j$
U	mean velocity
$\tilde{u}$	coherent component of velocity
u'	fluctuating component of velocity
x	axial distance
δ	displacement thickness
θ	momentum thickness
φ	azimuthal angle

<u>Subscripts:</u>

D	based on nozzle diameter
j,o	jet exit
θ	based on momentum thickness

INTRODUCTION

In a jet excited by naturally occurring disturbances, the large scale coherent structures occur over a band of frequencies and over various azimuthal mode numbers. The presence of these structures has been frequently characterized by correlation functions (Drubka, 1981; Sreenivasan, 1984; Chan, 1977; Gutmark et al., 1988). Correlations of streamwise velocity with circumferential separation can indicate the relative dominance of the axisymmetric or the azimuthal waves. For example, the correlations are independent of circumferential separation if the flow consists of circular vortex rings. If the correlations show a circumferential dependence it may be due to azimuthal waves developing on the circular vortex rings, or by a transverse flapping of the jet. The modal spectrum representation (Petersen et al., 1987) provides the capability of resolving the naturally occurring axisymmetric and azimuthal modes over a range of frequencies. One of the contributions of the present work is the use of this modal frequency spectrum representation to study naturally occurring instabilities in a high Reynolds number (Re(D) = 400 000) jet for both laminar and turbulent nozzle exit conditions.

The motivation for studying the naturally occurring modes is the identification of target modes to be artificially excited in order to enhance mixing rates in jets. In a previous paper (Raman et al., 1988), results were reported for an experiment that looked at the limit of jet mixing enhancement by single frequency, plane wave excitation. These experimental results were also compared with the predictions of a theoretical model (Mankbadi and Liu, 1981). The potential for two-frequency plane wave excitation to overcome the limitations of single frequency plane wave excitation has been demonstrated (Ho and Huang, 1982; Raman and Rice, 1989). However, two-frequency plane wave excitation also has its limitations since axisymmetric waves are damped beyond the potential core (Batchelor and Gill, 1962; Morris, 1976). Control in the region downstream of the potential core can be gained only by forcing modes that are amplified in that region. The second contribution of the present work is the description of an effort to control an extended region of the jet by forcing combinations of both axisymmetric and helical modes.

EXPERIMENTAL APPARATUS

The jet facility consists of a plenum tank containing flow straighteners and acoustic treatment. The plenum tank is supplied by pressurized air, which is exhausted into the room through an 8.89 cm nozzle. The turbulence intensity measured at the jet exit was about 0.1 percent and the acoustic treatment within the plenum eliminated most of the valve noise. Figure 1(a) is a photograph of the facility with the azimuthal mode excitation apparatus. The picture shows the external driver ring holding 8 acoustic drivers circumferentially mounted around the jet nozzle. The forcing of the azimuthal modes was accomplished by varying the amplitude and phase of the signals input to these drivers. The plane wave forcing was provided by an acoustic driver located in the plenum chamber. Figure 1(b) is a photograph of the facility with the radial traversing ring. The radial traversing ring is a large scale version of the apparatus which was originally designed at the University of Arizona (Petersen et al., 1987; Cohen and Wygnanski, Part I, 1987; Cohen and Wygnanski, Part II, 1987).

Measurements of unsteady streamwise velocity at various azimuthal locations were made using 8 hot-wires positioned at intervals of 45° about the circumference of the ring. The radial traversing ring was used to move the 8 hot-wires simultaneously in the radial direction. For the turbulent nozzle exit boundary layer case, a boundary layer trip ring was located 33 cm upstream of the nozzle exit, where the diameter of the contracting section was 13.1 cm. The nozzle ended with a sharp edge and had a 22 cm long cylindrical section prior to the exit. The trip ring had 82 saw teeth which protruded 4.76 mm into the flow. Without the trip ring, the exit boundary layer was laminar.

EXPERIMENTAL PROCEDURE

The 8 hot-wires were calibrated in situ against a pitot probe positioned at the jet exit. A fourth order polynomial was used to fit the calibration data. The desired forcing conditions at the nozzle exit were produced as follows: An 8 channel signal generator was used to produce variable amplitude and variable phase signals at a prescribed frequency. These signals were then amplified and input to the acoustic drivers. The unsteady velocity perturbation caused by the acoustic excitation was measured at the jet exit $\left(at\ \frac{x}{D} \approx 0, \frac{U}{U_{\mathfrak{C}}} = 0.8\right)$ using 8 hot-wire probes and the modal content was determined. The iterative fine tuning of the inputs and measurement of the modal content at the jet exit was continued until satisfactory forcing conditions were obtained. The acquisition of time series data from 9 channel (8 sensors and 1 reference) was accomplished using an HP multiprogrammer and a 500 KHz analog-to-digital conversion card. The measurement range was set to be -10 to +10 V. With a 12-bit resolution, the range is subdivided into 4096 bins, each bin being 0.00488 V in width.

INITIAL CONDITIONS

The experiments were conducted at a nozzle exit Mach number of 0.2 and a Reynolds number based on jet diameter (Re(D)) of 400 000. The measured nozzle exit mean radial velocity profile was approximately top hat in shape, and the rms profile was uniform in the jet core at the nozzle exit. For the untripped boundary layer, measured 0.5 mm downstream of the nozzle exit the momentum thickness (θ/D) shape factor (δ/θ), and peak fluctuation level (u'/U(%)) were 0.03, 2.0, and 15 respectively. In the absence of the trip ring the jet was, therefore, considered to have developed from a "nominally laminar" boundary layer.

For the tripped boundary layer case the corresponding values of θ/D, δ/θ, and u'/U(%) were 0.06, 1.6 and 6 respectively. The jet was, therefore, considered to have developed from a "nominally turbulent" boundary layer. Streamwise velocity spectra measured on the jet centerline and within the boundary layer, where the maximum fluctuations occurred, showed no distinct peaks. This indicated that the flow was reasonably "clean" and free of tones from valve and flow noise. The exit boundary layer spectrum also showed that there were no remnants of organized shedding from the tripping device. Detailed measurements of the initial conditions were reported in a previous paper (Raman et al., 1989).

THE MODAL SPECTRUM REPRESENTATION

The modal decomposition representation at a discrete frequency of the spectrum can be used to characterize the flow as consisting of various modes of motion of the vortical structures at that frequency. When the modal decomposition is performed at every frequency of the spectrum, a modal frequency spectrum is generated for each mode. The modal spectrum was generated by measuring the unsteady streamwise velocity using 8 hot-wires positioned at intervals of 45° about the circumference of the jet cross-section. Linearized signals from the hot-wires were input to a spectrum analyzer to obtain cross-spectra. Using the signal from hot-wire number 1 as reference, 7 cross-spectrum magnitudes and phases were obtained. Figures 2(a) to (d) show a sample for one pair where the signals from hot-wires numbers 1 and 2 (separated circumferentially by 45°) were used. The probes were at $x/D = 3$ in the core of the jet($r/D = 0.2$). The cross-spectral magnitude, figure 2(c), indicates a range of frequencies where signals from numbers 1 and 2 have content in common. The cross-spectral phase, figure 2(d), is an indication of the average phase difference between the two signals. The cross-spectra are randomly triggered ensemble averages over a long time interval. The 7 cross-spectra were decomposed into the axisymmetric mode, the first 3 modes in the clockwise direction and the first 3 modes in the anticlockwise direction.

The decomposition equation is:

$$F_k(\varphi_k) = a_o + \sum_{m=1}^{3} a_m e^{im\varphi_k} + \sum_{m=1}^{3} b_m e^{-im\varphi_k} \qquad k = 1,7$$

where F is the velocity cross-spectral function (magnitude and phase), φ is the known azimuthal angle, between the reference hot-wire and each of the other hot-wires. a_o is the coefficient for $m = 0$, a_1 is the coefficient for $m = +1$, b_1 is the coefficient for $m = -1$ and so on. With the 7 cross-spectra (magitudes and phases) as inputs the magnitude and phase of each of the 7 modes were determined, by solving the 7 complex equations. To generate the modal spectrum, the decomposition is performed at every frequency in the chosen range. The modal spectrum then consists of the amplitude of the mode plotted as a function of frequency.

NATURALLY OCCURRING MODES IN UNEXCITED JETS

The modal decomposition, performed at every 5 Hz up to 1000 Hz using 8 circumferential measurements, provided the magnitude of modes $m = 0, \pm 1, \pm 2, \pm 3$ as a function of frequency. For the jet excited by natural disturbances, the energy content of higher order modes ($m > 1$) was significantly lower than the axisymmetric and $m = \pm 1$ modes. Therefore, the results discussed in this section will only focus on modes $m = 0$ and $m = \pm 1$ for both laminar and turbulent nozzle exit conditions.

Many investigations have established that the development of a jet and its susceptibility to excitation depend considerably on the initial conditions (Hill et al., 1976; Hussain and Zedan, 1978; Gutmark and Ho, 1983). It is useful to compare the evolution of jets with turbulent and laminar nozzle exit boundary layers using the modal spectrum technique. Figures 3 and 4 show the downstream evolution of the modal spectra for jets with laminar and turbulent nozzle exit conditions, respectively. From these figures the preferred frequency concept can be generalized to include unexcited jets (for axisymmetric and helical modes). Figures 3(a) and (b), show that the axisymmetric mode is dominant in the initial region. But beyond the end of the potential core, the helical modes predominate (figs. 3(c) and (d)). The damping of the axisymmetric mode beyond the potential core in figures (3) and (4) is in agreement with the predictions of Batchelor and Gill (1962) and Morris (1976). Note in figures (3) and (4) that for instabilities triggered by natural disturbances, there is an equal probability of finding both $m = +1$ and $m = -1$ modes, due to the symmetry of the geometry. The preferred mode for natural instabilities, determined based on the highest amplitude attained by any wave in the spectrum, is around a St(D) of 0.5 for the axisymmetric mode. The corresponding St(D) for helical modes is 0.2. These values apply for both the laminar and the turbulent initial boundary layer cases.

A comparison of figures 3 and 4 shows that the growth of both axisymmetric and azimuthal waves occurs earlier for the laminar boundary layer case than for the turbulent. The earlier appearance of azimuthal waves for the laminar boundary case was interpreted as follows: Jets with laminar exit boundary layers have spreading rates that are higher than those with turbulent exit boundary layers. In addition to this, in the present work, the measured peak velocity fluctuation levels in the boundary layer at the jet exit were 15 and 6 percent of the jet velocity for the laminar and turbulent cases, respectively. The laminar case was therefore subjected to higher levels of natural disturbances than the turbulent. This resulted in a higher spreading rate and a shorter potential core (laminar potential core ended at $x/D \simeq 4$, whereas the turbulent potential core extended to $x/D \simeq 6$). Finally, it is the shorter potential core (earlier change in the shape of the velocity profile) that allows the jet in the laminar case to support helical disturbances closer to the nozzle exit than the turbulent. A more detailed explanation, Zaman (1991), indicates that the higher disturbance level for the laminar boundary layer case could be due to the coupling of unstable Tollmien-Schlichting waves in the nozzle boundary layer with the Kelvin-Helmholtz waves in the shear layer.

Figure (5) shows a comparison of the turbulent and laminar boundary layer cases for $x/D = 2$ and 4. In this figure, the data from figures (3) and (4) are plotted on a logarithmic ordinate to make the low amplitude (but rapidly growing) azimuthal modes visible. The stability analysis of Strange and Crighton, 1983, predicted that helical waves would be more amplified than axisymmetric waves at the preferred frequency. This finding is corroborated by the data in figures 5(a) and (b). Even though the helical modes have a higher growth rate, the initial region of the jet is dominated by the axisymmetric mode. This is attributed to the type of natural disturbances occurring at the jet lip. For the 8.89 cm nozzle used the cutoff frequency for all nonaxisymmetric modes was 2270 Hz (Skudrzyk (1971), page 431). Therefore acoustic disturbances in the frequency range of 0 to 1000 Hz arriving at the jet lip through the nozzle are axisymmetric. Some of these disturbances are of a relatively high amplitude (due to plenum resonances) and they couple with naturally occurring disturbances in the initial region of the shear layer. Therefore the axisymmetric "natural excitation" is much higher than the azimuthal "natural excitation" and this in turn causes the initial region of the jet to be dominated by the axisymmetric mode.

Sample mode spectra have been reported previously (Petersen et al., 1987) but have not been used to characterize the evolution of the various instability modes triggered by natural disturbances. There have been several other investigations of instability modes in jets with low amplitude excitation (Kusek et al., 1989; Corke et al., 1985). In these studies, a very low level of excitation was used to organize shear layer instabilities and to raise the large scale coherent structures over the background levels, in addition to providing a phase reference for the measurements. Even though the levels of excitation were of the same order as the naturally occurring fluctuations, the jet displayed different characteristics. For example, in the work of Corke et al., 1985, low amplitude acoustic excitation of the jet at the natural fundamental frequency of the axisymmetric mode suppressed the occurrance of the helical modes observed by Drubka, 1981, in the same jet facility. For this reason, the present work did not use low amplitude acoustic excitation.

Drubka (1981) found that when the disturbance level in the laminar exit boundary layer was of the order of 5 percent the probability of finding either mode (0 or 1) was 0.5, near the nozzle exit $\left(\frac{x}{D} < 1\right)$. The findings of the present work show clearly that the region up to the end of the potential core was dominated by the axisymmetric mode and only further downstream was the helical mode dominant. The reason for the apparent disagreement with the findings of Drubka (1981) is not known at this time and is currently being investigated.

COMBINATION OF PLANE WAVE AND AZIMUTHAL MODE EXCITATION

Based on the results presented thus far, plane wave excitation would be expected to be effective mainly in the region up to the end of the potential core. Since beyond this point, the axisymmetric mode is damped. Control of the region beyond the potential core could be accomplished via forcing the helical modes. Hence, a combination of both plane wave and helical mode forcing would be expected to be even more effective for controlling the jet than either excitation applied alone. Results will be shown for two cases with both having a turbulent nozzle exit boundary layer.

Figure 6(a) shows the evolution of modes for forcing case 1: $m = \pm 1$ at $St(D) = 0.15$, and $m = 0$ at $St(D) = 0.6$. The forcing here is in the range of the naturally preferred frequencies determined from the modal spectrum for the unforced jet. The forcing levels measured at $U/U_{\mathrm{¢}} = 0.8$, $x/D \simeq 0$ were $(\tilde{u}_o/U)_{St(D) = 0.6,\ m = 0} = 0.06$ and $(\tilde{u}_o/U)_{St(D) = 0.15,\ m = \pm 1} = 0.02$. The modal decomposition technique used for generating these results is the same as that for the unexcited case. However only the phase averaged coherent part of the signal at the excitation frequency was used. In the initial region $m = 0$ grows to about 9 percent of the jet exit velocity. Note that the modes in figure 6(a) are evolving in the presence of each other. Figure 6(a) shows that the $m = 0$ mode is amplified and saturates in the initial region of the jet. As the $m = 0$ mode becomes damped, the $m = \pm 1$ (denoted by a single curve) modes grow and peak around $x/D = 6$, beyond which they are damped. Figure 6(b) shows the momentum thickness plotted versus axial distance. The momentum thickness is calculated using:

$$\theta = \int \frac{U}{U_j}\left(1 - \frac{U}{U_j}\right)dr$$

Curves are shown for the following cases: unexcited; plane wave ($m = 0$) $St(D) = 0.6$) helical modes ($m = \pm 1$; $St(D) = 0.15$); and case 1 ($m = 0$ at $St(D) = 0.6$ and $m = \pm 1$ at $St(D) = 0.15$). The last two cases are represented by bands bounded by θ_{max} and θ_{min} since θ varies azimuthally. Comparing figures 6(a) and the curves for case 1 in figure 6(b) one observes that the local regions of higher spreading rate (steeper curves in figure 6(b) for x/D between 0 and 2, 4 and 6) correspond to regions of wave amplification in figure 6(a) and local regions of lower spreading rates (flattening of curves in figure 6(b), for x/D between 2 and 4, greater than 6) correspond to regions where the waves are damped. The jet's spreading rate is enhanced in a 2 step process. In step 1, due to $m = 0$ (x/D between 0 and 2), and in step 2, due to $m = \pm 1$ (x/D between 4 and 6). The above interpretation is also supported by the theory of Mankbadi and Liu, 1981.

Figures 7(a) to (c) show the same type of data for forcing case 2: $m = \pm 1$ at $St(D) = 0.3$ and $m = 0$ at $St(D) = 0.6$. The forcing conditions here correspond to the Craik-triad case (Craik, 1971). The forcing levels measured at $U/U_{\mathbb{C}} = 0.8$, $x/D \simeq 0$ were $(\tilde{u}_o/U)_{St(D) = 0.6,\ m = 0} = 0.06$ and $(\tilde{u}_o/U)_{St(D) = 0.3,\ m = \pm 1} = 0.06$. The interpretation for figures 7(a) and the curves for case 2 in figure 7(b) is the same as for case 1 in figures 6(a) and (b), but unlike case 1, the $m = \pm 1$ peaks occur at around $x/D = 3$ (but persist beyond the potential core at levels higher than $m = 0$). The growth of the $m = 0$ mode is responsible for the enhanced spreading rate up to $x/D = 2$, while beyond $x/D = 3$ it is the flapping caused by the $m = \pm 1$ that enhanced further mixing. The main difference between cases 1 and 2 is the choice of the excitation frequency for the $m = \pm 1$ modes (case 1, $St(D) = 0.15$ and case 2, $St(D) = 0.3$) the axisymmetric mode being the same for both cases. The effect of this choice is seen while comparing cases 1 and 2 in figures 6(b) and 7(b). The low frequency helical modes along with the axisymmetric mode of case 1 (fig. 6(b)) are more effective in producing higher spreading rates in the downstream region ($5 < x/D < 10$) whereas higher frequency helical modes along with the same axisymmetric mode in case 2 (fig. 7(b)) cause a rapid increase in the spreading rate around $x/D = 3$ and are most effective in the initial region ($1 < x/D < 5$). Therefore the choice of the forcing frequency would vary depending on the region over which maximum control is desired.

Figure 7(c) shows mean velocity data in the form of contour plots for the unexcited jet and for forcing case 2 at various cross-sections of the jet. Because there are only 8 circumferential measurement stations, the plots look octagonal. The outermost contour was chosen to be the 20 percent velocity contour (velocity is 20 percent of the jet exit velocity) as measurements near the outer edge of the jet are unreliable due to flow reversals. The contours for the unexcited jet in figure 7(c) are seen to be axisymmetric for all x/D locations. When the jet is excited by multiple modes, a higher spreading rate (as evidenced by a larger cross-sectional area in figure 7(c)) is observed. From figures 6 and 7 it is clear that the combination of a plane wave and two opposing helical modes provides a higher degree of control over the spreading rate of the jet than either excitation applied alone the plane wave enhances mixing up to the end of the potential core, and helical modes ($m = \pm 1$) cause the jet to flap beyond the potential core.

CONCLUDING REMARKS

1. The evolution of instabilities resulting from naturally occurring disturbances at the jet lip was studied using the modal frequency spectrum. The region up to the end of the potential core was dominated by the axisymmetric mode. The azimuthal modes grew rapidly but dominated only after the potential core region.

2. The growth of the azimuthal modes was observed closer to the nozzle exit for the jet in the laminar boundary layer case than for the turbulent. This was interpreted as follows: In the laminar boundary layer, higher fluctuation levels were measured at the jet exit. This resulted in a shorter potential core, a higher spreading rate, and an earlier appearance of the azimuthal modes.

3. Forcing combinations of multiple frequencies and multiple modes provides a higher degree of control over the spreading rate of the jet. When the combination is applied, the plane wave enhances mixing in the region up to the end of the potential core, and the helical modes ($m = \pm 1$) cause the jet to flap beyond the potential core. In this way, the region of control is extended.

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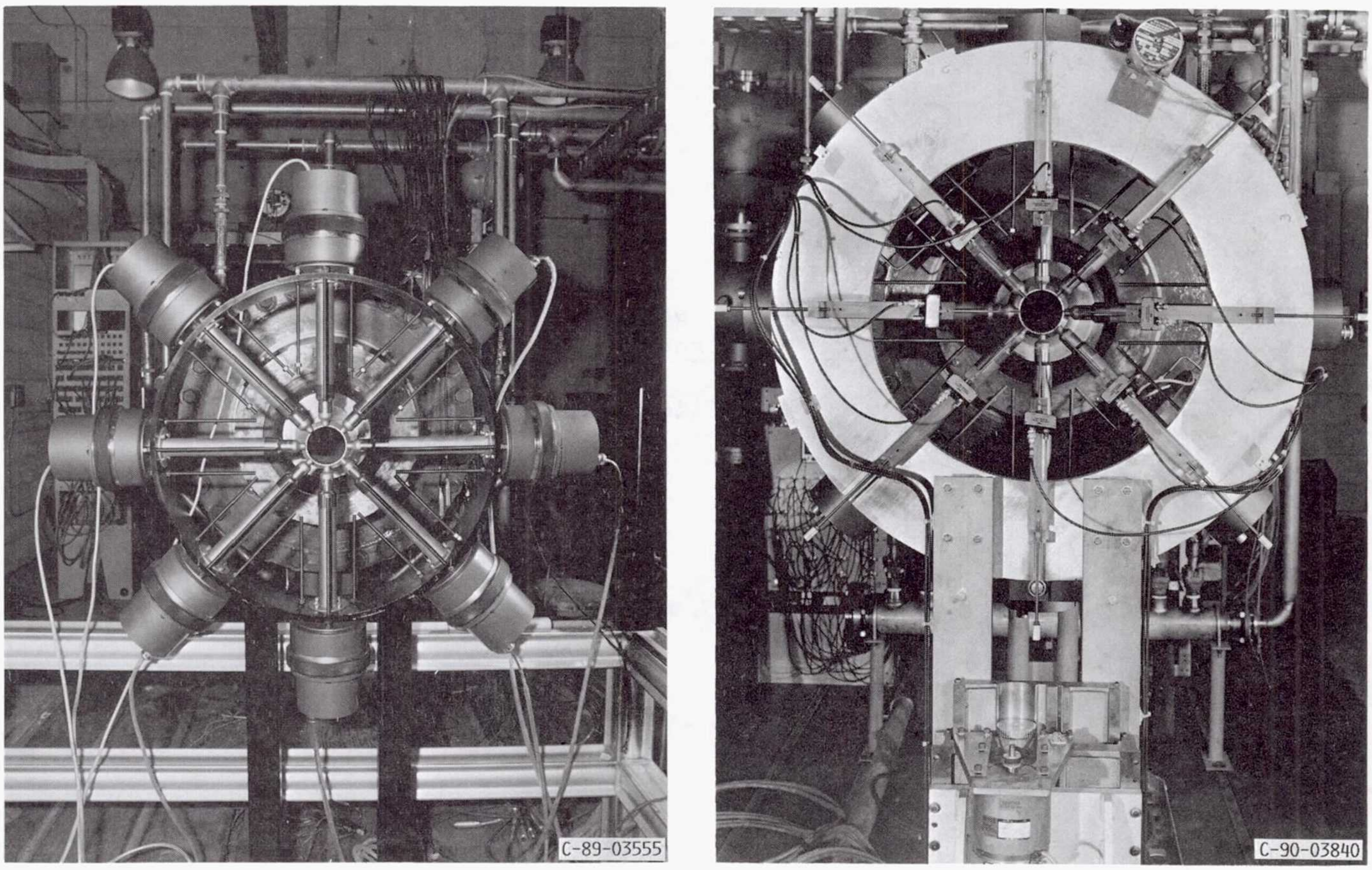
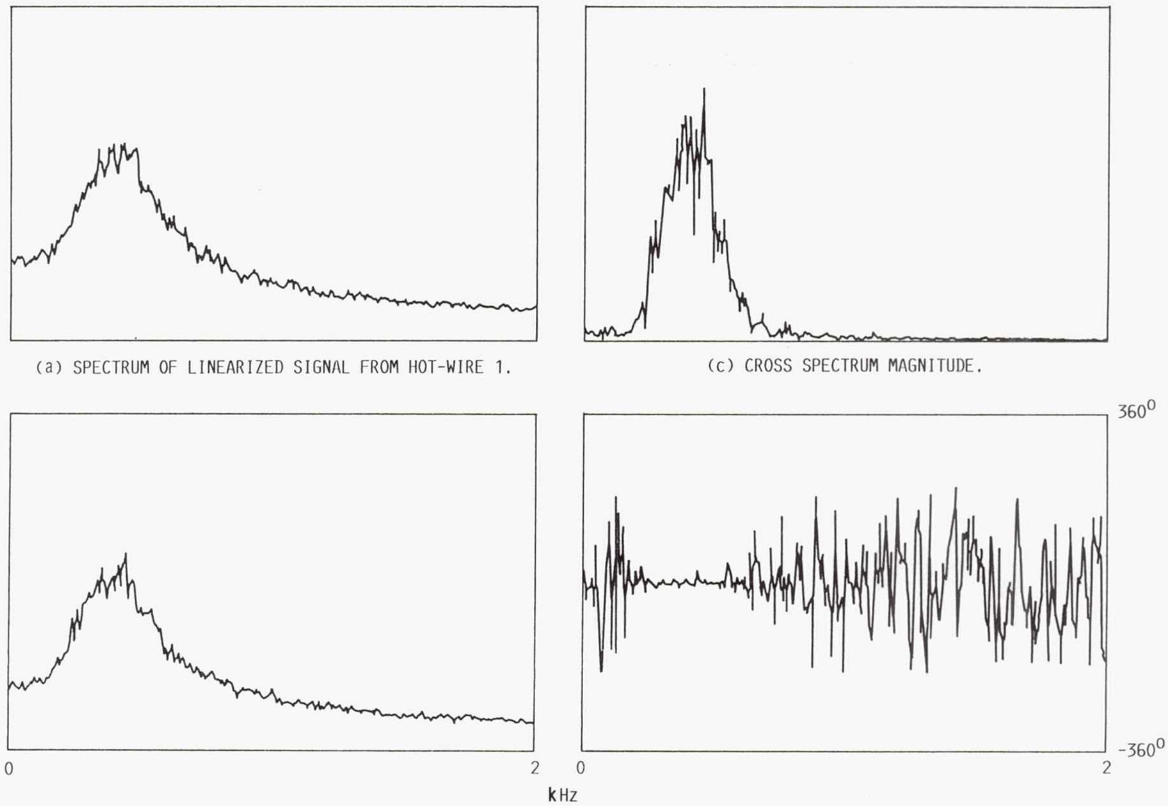


(a) JET FACILITY WITH AZIMUTHAL MODE EXCITATION APPARATUS.

(b) JET FACILITY WITH AZIMUTHAL MODE MEASUREMENT APPARATUS.

FIGURE 1. - JET EXCITATION APPARATUS.



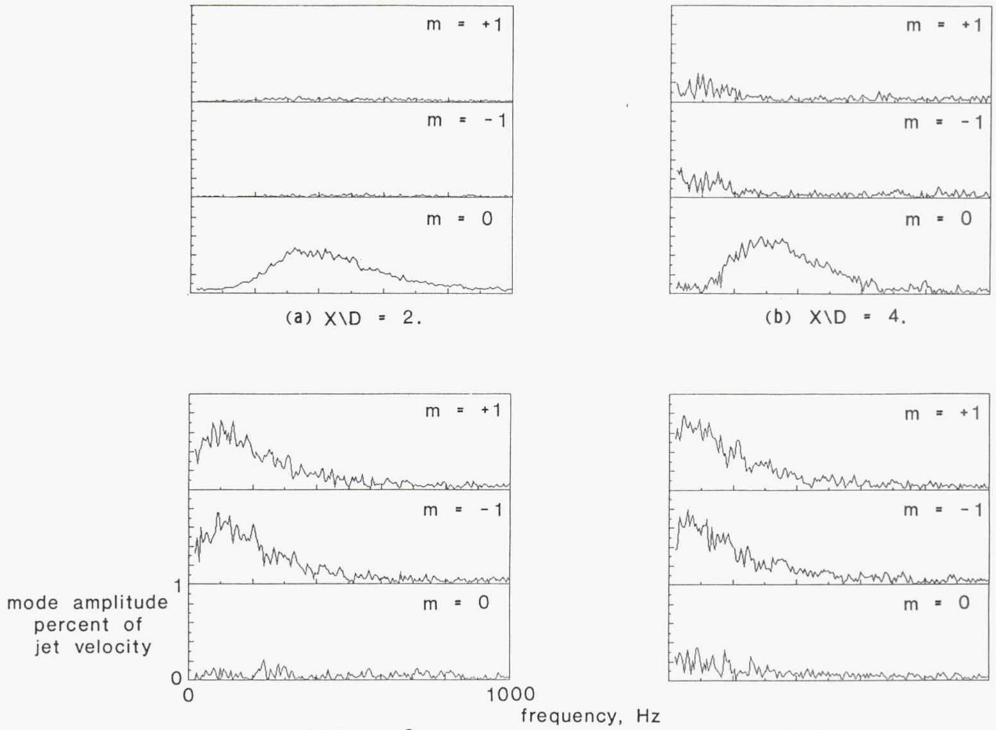
(a) SPECTRUM OF LINEARIZED SIGNAL FROM HOT-WIRE 1.

(b) SPECTRUM OF LINEARIZED SIGNAL FROM HOT-WIRE 2.

(c) CROSS SPECTRUM MAGNITUDE.

(d) CROSS SPECTRUM PHASE.

FIGURE 2. - UNEXCITED JET CROSS-SPECTRUM AT X/D = 3, $\frac{U}{U_{\mathbb{C}}}$ = 0.8, M = 0.2, Re(D) = 400 000.



(a) X\D = 2.

(b) X\D = 4.

(c) X\D = 6.

(d) X\D = 8.

FIGURE 3. - AXIAL EVOLUTION OF THE NATURAL MODES IN A CIRCULAR JET, LAMINAR INITIAL BOUNDARY LAYER. VELOCITY MEASUREMENTS AT $\frac{U}{U_{\mathbb{C}}}$ = 0.8, M = 0.2, Re(D) = 400 000.

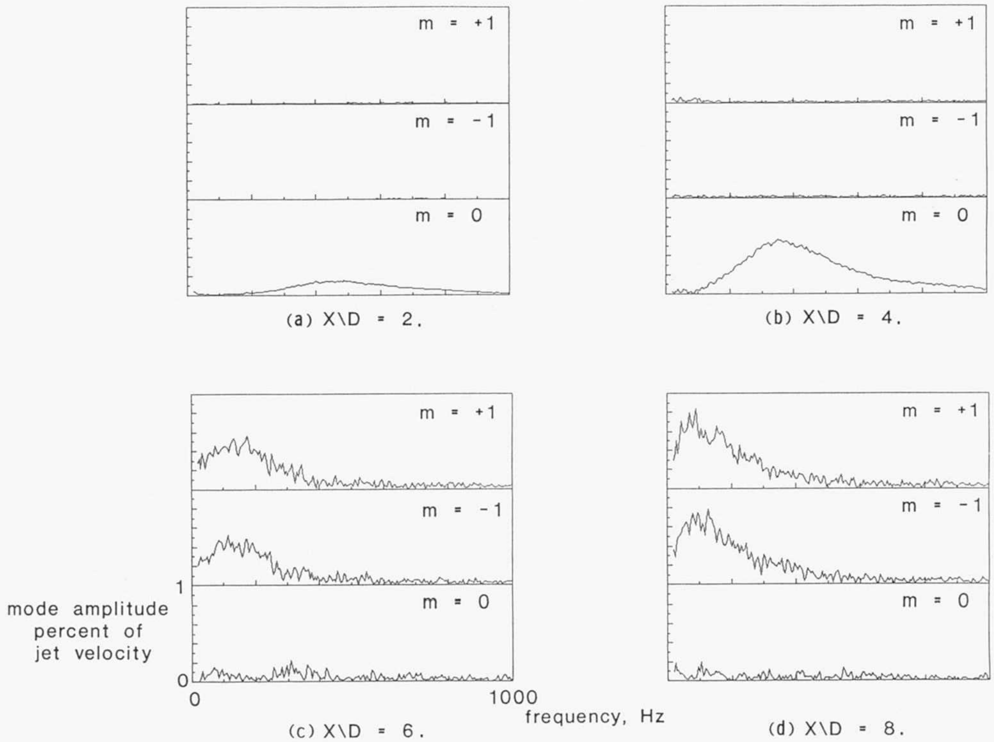
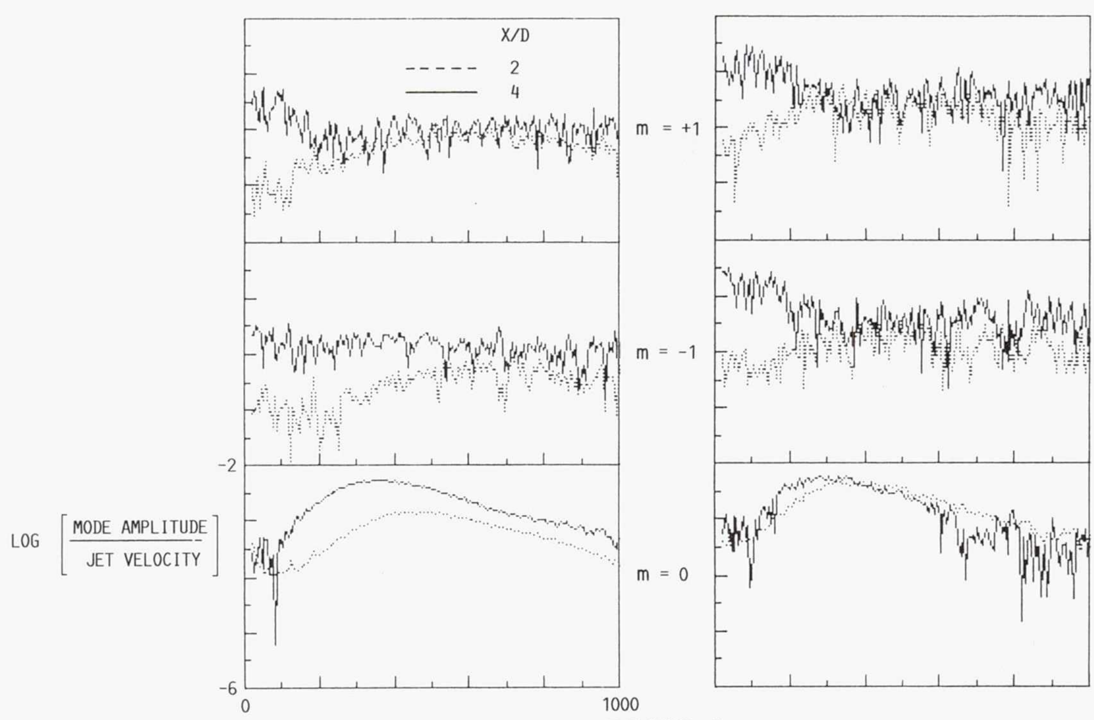
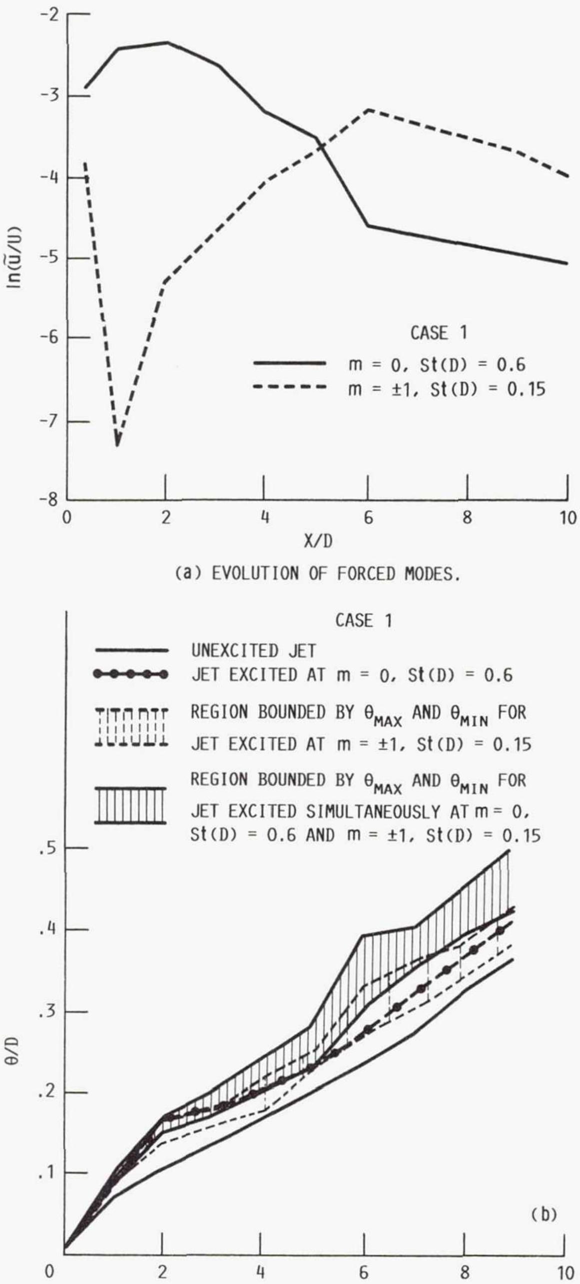


FIGURE 4. - AXIAL EVOLUTION OF THE NATURAL MODES IN A CIRCULAR JET, TURBULENT INITIAL BOUNDARY LAYER. VELOCITY MEASUREMENTS AT $\frac{U}{U_{℄}}$ = 0.8, M = 0.2, Re(D) = 400 000.



(a) TURBULENT EXIT BOUNDARY LAYER. (b) LAMINAR EXIT BOUNDARY LAYER.

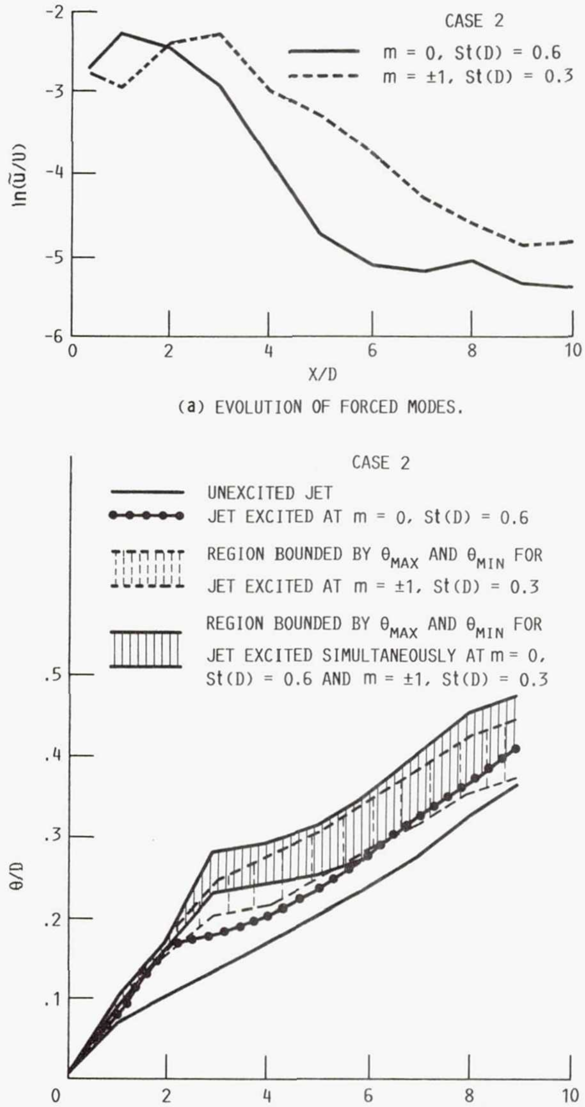
FIGURE 5. - AXIAL EVOLUTION OF THE NATURAL MODES IN A CIRCULAR JET, TURBULENT VERSUS LAMINAR INITIAL BOUNDARY LAYER. VELOCITY MEASUREMENTS AT $\frac{U}{U_{℄}}$ = 0.8, M = 0.2, Re(D) = 400 000.



(a) EVOLUTION OF FORCED MODES.

(b) DEVELOPMENT OF MOMENTUM THICKNESS.

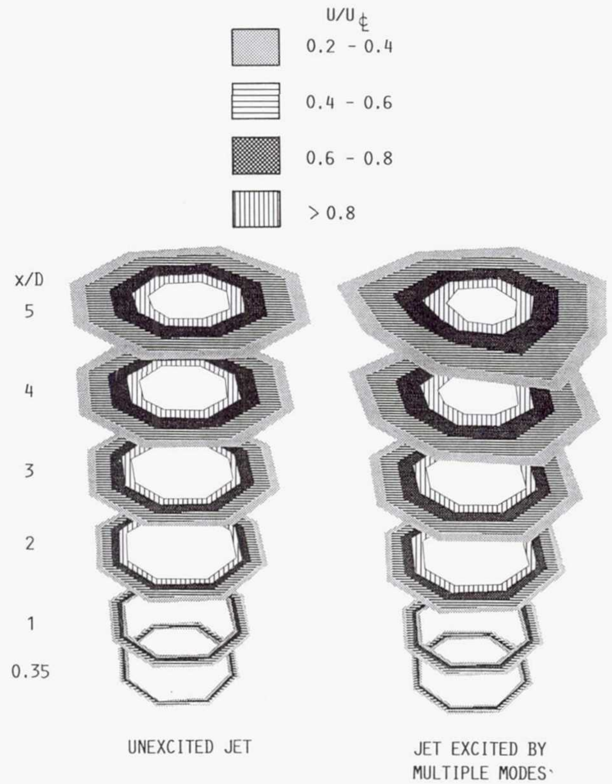
FIGURE 6. - MULTI-MODAL EXCITATION RESULTS FOR CASE 1 (FORCING LEVELS, $(\tilde{u}_0/U) = 0.06$ (St(D) = 0.6, m = 0) $(\tilde{u}_0/U) = 0.02$ (St(D) = 0.15, m = ±1)).



(a) EVOLUTION OF FORCED MODES.

(b) DEVELOPMENT OF MOMENTUM THICKNESS.

FIGURE 7. - MULTI-MODAL EXCITATION RESULTS FOR CASE 2 (FORCING LEVELS, $(\tilde{u}_0/U) = 0.06$ (St(D) = 0.6, m = 0) $(\tilde{u}_0/U) = 0.06$ (St(D) = 0.3, m = ±1)).



(c) JET MEAN VELOCITY CONTOURS.

FIGURE 7. - CONCLUDED.

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15. Supplementary Notes

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16. Abstract

Naturally occurring instability modes in an axisymmetric jet were studied using the modal frequency spectrum technique. The evolution of the modal spectrum was obtained for a jet with a Reynolds number based on diameter (Re(D)) of 400 000, for both laminar and turbulent nozzle boundary layers. In the early evolution of the jet the axisymmetric mode was predominant, with the azimuthal modes growing rapidly but dominating only after the end of the potential core. The growth of the azimuthal modes was observed closer to the nozzle exit for the jet in the laminar boundary layer case than for the turbulent. Based on the results from these naturally occurring jet instability mode experiments, target modes for efficient excitation of the jet were determined and two cases of excitation were studied: First, the jet was excited simultaneously by two helical modes, $m=+1$ and $m=-1$ at a Strouhal number based on jet diameter (St(D)) of 0.15 and the axisymmetric mode, $m=0$ at a St(D) of 0.6. Second, $m=+1$ and $m=-1$ at St(D)=0.3 and $m=0$ at St(D)=0.6 were excited simultaneously. The downstream evolution of the hydrodynamic modes and the spreading rate of the jet were documented for each case. Higher jet spreading rates, accompanied by distorted jet cross-sections were observed for the cases where combinations of axisymmetric and helical forcings were applied.

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